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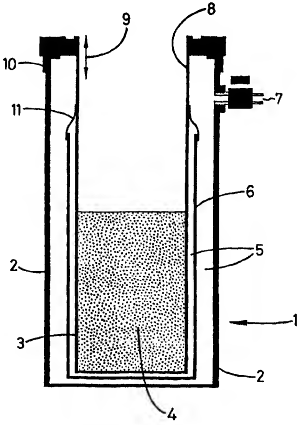
(54) Title: LIQUIFIED GAS CRYOSTAT

(57) Abstract

A liquified gas cryostat having an inner wall (3) to contain the liquified gas (4) and an other wall (2) spaced therefrom is provided, in the space between the two walls, with multilayered insulation (5), formed by coating a woven fabric with a thin layer of gold or aluminium to create small, self-defined areas of metallization, and the space is evacuated. Also in the space is located at least one radiation shield (6) of material which exhibits high thermal conductivity and negligible electrical conductivity. The shield (6) extends beneath and is continuous around the inner wall (3) over the volume intended to be occupied by the liquified gas and may be vapour-cooled or cryo-cooled. Where more than one shield is used, both or all of them may be vapour-cooled or cryo-cooled. Alternatively, one or more of the shields may be vapour-cooled and the remainder cryo-cooled.



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LIQUIFIED GAS CRYOSTAT

The present invention relates to a liquified gas cryostat and particularly to liquid helium cryostats.

In a conventional magnetic resonance imaging (MRI) system, which operates at a static field strength of approximately 1 Tesla, and a corresponding Larmor frequency 42.5 MHZ, most of the noise which degrades the final image quality is caused by eddy current losses in the sample (patient). These losses can be treated as an effective additional series resistance in the receiver coil, R_{samp}, at the sample temperature, T_{samp}. R_{samp} scales with the 4^{th} or 5^{th} power of the sample radius and with the square of the operating frequency of the MRI system.

In a low field system, operating below approximately 0.1 Tesla, the sample losses can become less significant than the intrinsic losses in the receiver coil, particularly if a surface coil of small dimensions is used. The coil is tuned to the NMR (Larmor) frequency with a capacitor. The receiver coil and its tuning capacitance have a total intrinsic resistance R_{coil}, which is maintained at a temperature T_{coil} (normally room temperature). R_{coil} generates an r.m.s. noise voltage given by:-

$$V_n=\sqrt{4k_BT_{coil}R_{coil}\Delta f} \qquad (1)$$

where k_B is Boltzmann's constant and Δf is the measurement bandwidth. The signal to noise ratio (SNR) of an NMR receiver can be expressed in terms of the coil and sample parameters as:-

$$SNR \propto \frac{\omega_l^2 B_1}{\sqrt{R_{coil}T_{coil} + R_{samp}T_{samp}}} \qquad (2)$$

where ω_L is the Larmor frequency of the NMR system, which is proportional to the main field strength, and B_1 is a parameter which describes the magnetic coupling between the sample and the receiver coil (D.I. Hoult and P.C. Lauterbur, J. Magn. Reson. 34, 425-433 (1979)).

If it is the case that the coil is the dominant system noise source it follows from Eqn. 2 that by reducing its temperature and resistance the system SNR can be improved. There is considerable interest at present in the development and use of surface coils fabricated from high temperature (High-T_c superconducting materials). These are cooled below their superconducting transition temperature (T_c) with liquid nitrogen at 77°K. Liquid nitrogen is easy to handle and can be held in a very simple cryostat made from expanded polystyrene foam. The results obtained at 77 K with High-T_c coils are often disappointing because although the coil's noise is reduced, the preamplifier which follows the coil in the receiver chain may generate too much noise in itself to realise the improvement. High-T_c coils have a further disadvantage that, at present, they must be fabricated epitaxially on a ceramic substrate in order to offer the best performance. There is not yet a high-T_c wire with good radio frequency (RF) characteristics which can easily be wound into suitable coil shapes.

Further improvements in coil performance can be obtained by using a low-T_c superconductor such as niobium. This is a refractory metal and is easily formed into coils of any required shape. Its low transition temperature of approximately 9 K requires that it be cooled in liquid helium at 4.2 K. From Eqn. 1 it is apparent from the temperature ratio that the r.m.s. noise voltage produced by a resistance at 4.2 K should be a factor of approximately 4.3 less than that produced by the same resistance at 77 K. Although superconducting coils are used, the capacitors used to tune them will always give rise to some resistance which reduces

on cooling, so the expected improvement factor is greater than the temperature ratio suggests. At such low temperatures a very high performance amplifier is required to match to the low noise coil. For many years the SQUID (Superconducting Quantum Interference Device) has been used as a low noise preamplifier for solid-state NMR experiments. The SQUID is the most sensitive magnetic field detector yet devised (it is the only device, for example, capable of detecting the magneto-encephalogram (MEG) - the minute magnetic signals generated by brain activity).

Research has been conducted into using low-T_c receiver coils with SQUID amplifiers to improve the SNR of low field NMR (MRI) performed on room temperature samples positioned outside the cryostat, for example, in Phys. Med. Biol. 37 2133-2137 (1992) and in IEEE trans. Appl. Supercon 5. 3218-3221 (1995) (both to H.C. Seton et al). A further relevant publication is "A 4.2 K receiver coil and SQUID Amplifier used to improve the SNR of magnetic resonance images of the human arm, in Meas.Sci.Technol., 8, 198-207, 1997; by H.C. Seton et al. Unlike liquid nitrogen, liquid helium requires specialised handling and the design of cryostats to contain detectors provides challenging engineering and design problems. Relatively sophisticated insulation techniques are required to ensure that a cryostat's liquid helium hold-time is acceptable.

A commercially manufactured cryostat (Biomagnetic Technologies Inc.) intended for use in biomagnetism experiments is available. This cryostat normally has a hold time of 4.5 days; the time required for a fill of liquid helium (6 litres) to evaporate completely.

The cryostat is a double walled dewar vessel, with the space between the walls evacuated to eliminate gas conduction to the liquid helium volume. The walls are fabricated from glass reinforced plastic (g.r.p.) to minimize eddy current losses.

In addition, approximately 30 layers of multilayer insulation (MLI) typically of aluminized mylar are placed between the walls to reduce the radiative heat flux. The thin aluminium layer on this material has a very low emissivity and can be regarded as a heat reflector.

The rate of radiative heat transfer between a hotter surface at temperature T_{hot} (i.e. the outside wall of a cryostat at room temperature, 300 K) and a cooler surface at T_{cold} (i.e. the inside wall of a cryostat at liquid helium temperature, 4.2 K) is given by Stefan's Law which can be stated as:-

$$Q = \sigma \epsilon A \left(T_{hot}^4 - T_{cold}^4\right) \qquad (3)$$

where σ is Stefan's constant, ϵ is the emissivity of the surfaces and A is the area over which the radiative heat transfer is taking place. If N layers of MLI are interposed between the two walls at T_{hot} and T_{cold}, the radiative heat transfer given by Eqn. 3 is reduced by a factor of $1/(N+1)$. The layers of MLI reach thermal equilibrium mainly by radiative heat transfer and by conduction within a layer. The efficiency of the MLI layers can be greatly improved by inserting a third surface, called a radiation shield, or heat shunt, between the outer and inner walls at an intermediate temperature T_{sheild}. This shield can be cooled either by contact with a liquid nitrogen reservoir (at 77 K) or a cryo-cooler, or by being thermally anchored to a point on the tube venting the helium gas, sometimes called the cryostat "neck", evolved as the liquid helium boils off. The "cold end" of the vent tube is at a temperature near that of liquid helium (4.2 K). This rises along the tube's length almost to room temperature at the top of the cryostat so, in principle, any shield temperature in this range can be obtained by correct choice of anchoring position along the neck. The shield acts by intercepting the radiant heat flux from the outside wall of the cryostat (reduced by any intervening MLI layers) and conducting this heat to its anchor point on the venting tube.

This heat is now removed from the radiant flux into the liquid helium volume. The helium volume at temperature T_{cold} is now presented with a surface at T_{sheild} rather then at T_{hot} and Eqn.2 shows that if the shield temperature were 77 K the radiant flux would be reduced by approximately 230 times. However, part of this heat is returned to the helium volume because one must also take account of the additional heating of the venting tube by the heat shunt which will increase the conductive heat flux to the liquid helium. Either copper or aluminium is used to make radiation shields in a conventional cryostat, since each material has high thermal conductivity in the useful temperature region of 60-150 K (see Figure 1); Unfortunately the electrical conductivity of both these metals is also very high at low temperatures and gives rise to eddy current losses. Phys. Med. Biol. (1992) Vol. 37 No. 11 P2133-2137 reveals the detection of magnetic resonance signals at 425 kHz and a cryostat arrangement for use therewith.

Because magnetic fields are detected from outside the cryostat, the signals must pass through a vacuum gap and any insulation it contains. The conventional untuned SQUID magnetometer detector has a uniform response to magnetic fields from d.c. to a frequency determined by a roll-off filter in the input circuit (usually a few tens of kHz). Since the input circuit is superconducting, the detector sensitivity is largely governed by the SQUID's white noise level which, expressed as an equivalent flux noise, is typically $5\mu\Phi_0/\mathrm{Hz}^{\frac{1}{2}}$, where Φ_0 is the flux quantum, equal to $h/2e$. The magnetic field sensitivity depends on this SQUID noise, the SQUID's input coil inductance, input coil coupling coefficient and the pick-up coil geometry. A typical magnetometer exhibits a field sensitivity of approximately 5 $\mathrm{fT/Hz}^{\frac{1}{2}}$. The cryostat eddy current losses generate additional frequency-independent noise in this type of untuned, superconducting detector. A suitable cryostat design for this detector ensures that the noise level due to eddy current losses is below approximately 2 $\mathrm{fT/Hz}^{\frac{1}{2}}$ so that it is less than

the SQUID noise.

The tuned input circuit that is used with SQUID detectors permits magnetic field sensitivities of below 0.1 fT/Hz^{½} and so the cryostat noise must be reduced below this level. The ultimate detector sensitivity is set mainly by Johnson noise due to losses in the capacitor used to tune the input circuit to the required Larmor frequency, with only minor contributions from the SQUID amplifier's noise source. For this circuit, cryostat losses appear as an additional resistance which scales with the square of the Larmor frequency. When such a detector is used at a high frequency, these losses can reduce the circuit Q-factor dramatically and generate noise which exceeds that due to the intrinsic losses. Therefore special measures are required to reduce cryostat RF losses when tuned detector coils are used.

It has previously been found necessary to remove part of the insulation surrounding the end of the cryostat (which is formed into a narrow "tail") because the metal content of the MLI and the radiation shield gives rise to eddy current losses. These losses destroy any benefit gained from using a tuned detection coil cooled to such low temperatures.

It should be noted that cryostat manufacturers have already partially addressed the problem of eddy current losses. Rather than being made out of an unbroken copper cylinder, the shield in a typical commercial cryostat is formed from electrically insulated strips or wires of aluminium or copper. These are set lengthways into a g.r.p. tube. This construction ensures that the radiant heat incident on the shield is conducted efficiently up the length of the cryostat (it is not necessary to have good thermal conductivity circumferentially), but that the areas of any electrically conducting paths are kept to a minimum, since it is these which give rise to RF (eddy current) losses. Similarly, the metallisation on the MLI layers has been broken up into areas

of approximately 3 cm^2 to cut down the area of any conducting paths. These measures reduce cryostat noise to an acceptable level for use with untuned magnetometers, but the noise becomes excessive when tuned coils are used at high frequencies.

The present invention provides a new type of liquid helium cryostat with a cooled shield that exhibits low losses at radio frequencies.

According to a first feature of the invention therefore there is provided a liquified gas cryostat comprising:-

an evacuated housing having inner and outer walls provided with multi-layer insulation and a cooled radiation shield, said shield being continuous over the areas of the inner wall of the housing juxtaposed to the intended level of the liquified gas.

The invention is characterized in that the radiation shield is formed of an electrical insulator with high thermal conductivity but negligible electrical conductivity in the temperature range of intended use. The insulator may be selected from a sintered ceramic material, sapphire or diamond composite powder.

The sintered ceramic material may be alumina (Al_2O_3), aluminum nitride (AlN) or silicon carbide (SiC) for example. The liquified gas may be nitrogen or preferably helium.

The radiation shield is preferably operatively connected at or towards its intended upper end by means of a heat exchange strip which interconnects the upper portions of the shield with the inner wall of the housing. This heat exchange strip may be made of copper or aluminium and may be in the form of a continuous or discontinuous annulus. The radiation shield may alternatively be thermally isolated from the cryostat neck

and cooled by a cryo-cooler to extend the cryogen lifetime over that possible with the vapour-cooled shield.
The multi-layer insulation is metallized and is treated to provide an arrangement such that the metal layer is in discrete areas that do not exceed 2 mm by 2 mm.

In a preferred form of the invention, the insulation is preferably formed of a woven fabric, for example, a woven polyester fabric thinly coated with a metallized layer of gold or aluminium. Discontinuities in the metallisation arise because the thin metal coating is applied to a woven surface. Each time one thread crosses another, there is a "masked" region, one thread wide, which is not metallized. This metallized layer can be coated on both sides so long as there are discontinuities, but the layer is preferably coated on one side only of the woven material. The individual elements of the metallized layer may have an average size of approximately 500μm by 20μm. Indeed, areas of metallisation as small as 10μm x 300μm have been produced easily and cheaply by means of this technique. This provides a self-defined, highly uniform, low eddy current loss, reflective insulating material for use as superinsulation in cryostats. Although polyester woven filaments are suggested, any smooth woven filament with a low vacuum outgassing rate is suitable.

The invention will now be described by way of illustration only with reference to figures 1 and 2 of the drawings, wherein Figure 1 shows a graph of the thermal conductivity of various materials, and

Figure 2 shows a vertical cross-section through a liquid helium cryostat in accordance with the present invention.

With reference to Figure 2, there is provided a double walled dewar vessel housing 1 in which a space between the outer wall 2 and the inner wall 3 is evacuated via valve 7 to eliminate gas conduction into the liquid helium volume. The walls of

the dewar vessel 1 are fabricated from glass reinforced plastic (GRP) to minimize eddy current losses and closed at their upper ends by a vacuum seal 10. Disposed within the evacuated space are a plurality of approximately 30 to 60 layers of aluminised mylar multi-layer insulation 5 to reduce heat flux. Generally there tend to by more layers adjacent the side of the shield to minimize liquified gas boil off, and fewer layers near and covering the base to minimize RF losses near the detection coil. The thin aluminium layer on the mylar material has a very low emissivity and can be regarded as a heat reflector, but in accordance with the present invention should have discrete aluminised areas preferably of a size below 2 mm by 2 mm to prevent electrical conduction.

Disposed within the lower portion of the housing 1 is a radiation shield 6 formed of alumina ceramic. This is in this instance in the form of a right cylinder with the bottom secured such that the whole portion of the inner wall 3 over the portion which in use will be covered by liquid helium 4 is juxtaposed to the radiation shield 6. The upper portion of the radiation shield 6 is operatively interconnected by copper strips in the form of an annulus which extends between the outer face of the inner wall 3 and the outer face of the top of the radiation shield 6 towards the neck 8 of the cryostat.

The shield 6 thus takes the form of a tube with wall thickness of approximately 2 mm and a closed bottom end of the same thickness. This bottom end is machined as a separate piece (a 2 mm thick disc) and then glued to the tube with epoxy resin to form the closed end. The open end is then supported mechanically and firmly anchored to the cryostat neck using strips of copper 11 fixed with epoxy resin. The strips form a heat exchanger between the cold gas 4 boiling off from the liquid helium volume and the ceramic radiation shield 6. The presence of copper at the end of the cryostat neck 8 does not give rise to any significant eddy current losses in the

detector coil, and it will be appreciated that the position of the upper end of the copper strips defines the temperature of the shield which may be adjusted by altering the relative position 9 of the strip with regard to the open rim of the neck 8. The radiation shield may, alternatively, be thermally isolated from the cryostat neck and cooled by a cryo-cooler to extend the cryogen lifetime over that possible with the vapour-cooled shield.

Plural shields may be used and, in these circumstances, a mixture of vapour and cryo-cooling may be used if desired. Thus both or all shields may be vapour-cooled, both or all shields may be cryo-cooled or, depending upon how many shields are used, one or more may be vapour cooled and the remainder may be cryo-cooled, depending upon the desired operational factors and the performance and cost requirements of the system.

The arrangement shown in Figure 2 may be utilized with a SQUID as described in Phys. Med. Biol. reference described above.

The ceramic shield in accordance with the present invention is applicable to all types of low noise cryostats including those required for biomagnetism determinations. The cryostat has a reduced eddy current loss even in the biomagnetic frequency range and so would permit more sensitive measurements to be made if a more sensitive SQUID became available. The cryostat of the invention only requires refilling with liquid helium at the same frequency as conventional low boil-off types.

The main area of use is in NMR and MRI determination performed at room temperature on for example patients. In particular a liquid helium temperature tuned superconducting surface coil coupled to a SQUID detector operating in such a cryostat allows MR images with high SNR to be obtained at low field strength. This avoids the expensive requirement for a high

field imager and permits studies which can only be performed at low field strength to be performed satisfactorily. The invention therefore provides a cryostat comprising a ceramic radiation shield and in the alternative a cryostat comprising a metallized woven fabric insulator.

CLAIMS:

1. A liquified gas cryostat comprising an evacuated housing having inner and outer walls provided with metallized multi-layer insulation and a cooled radiation shield, said shield being continuous over the area of the inner wall of the housing juxtaposed in the intended level of the liquified gas;

characterized in that the radiation shield is formed of an electrical insulator with high thermal conductivity but negligible electrical conductivity in the temperature range of intended use.

2. A cryostat according to claim 1 wherein the electrical insulation is selected from a sintered ceramic material, sapphire or diamond power composite.

3. A cryostat according to claim 2 wherein the sintered ceramic is selected from alumina, aluminium nitride and silicon carbide.

4. A cryostat according to either of claims 2 or 3 wherein the liquified gas is selected from nitrogen or helium.

5. A cryostat according to any preceding claims wherein the radiation shield is vapour cooled, being operatively connected at or towards its upper end by means of a heat exchange strip, said strip interconnecting the shield with the inner wall of the housing.

6. A cryostat according to claim 5 wherein the heat exchange strip is formed of copper, aluminium or a ceramic material and is continuous or discontinuous.

7. A cryostat according to any of claims 1 to 4 wherein the radiation shield is cryo-cooled.

8. A cryostat according to any preceding claim wherein the insulation is metallized and is treated to provide an insulative layer such that the metallized portions thereof provide areas which do not exceed 2 mm by 2 mm.

9. A cryostat according to claim 8 wherein the insulation is formed of a woven fabric coated with a metallized layer.

10. A cryostat according to claim 9 wherein the metallized layer is coated from one or both sides such as to provide an average metallized element of approximately 500 μm by 20 μm.

11. A cryostat according to any preceding claim provided with a plurality of cooled radiation shields.

12. A cryostat according to claim 11 wherein said shields are vapour cooled.

13. A cryostat according to claim 11 wherein said shields are cryo-cooled.

14. A cryostat according to claim 11 wherein at least one of said shields is vapour-cooled and at least one other of said shields is cryo-cooled.

15. A liquified gas cryostat comprising an evacuated housing having inner and outer walls provided with metallized multi-layer insulation;

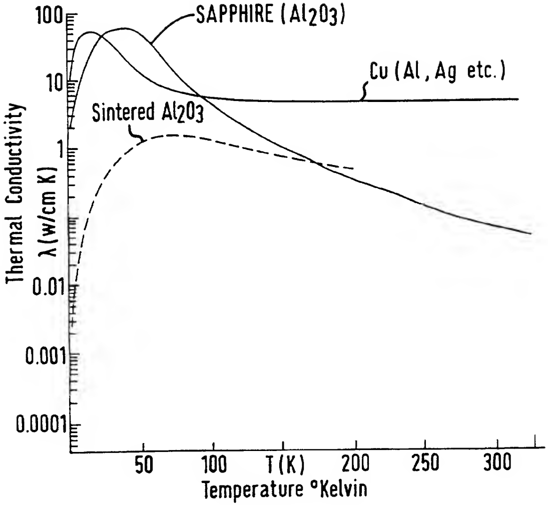
characterized in that the insulation is formed of a woven fabric coated with a metallic layer to create discrete, self defined areas of metallisation.

16. A cryostat according to claim 15 wherein said fabric is a polyester fabric.

17. A cryostat according to either of claims 15 or 16 wherein said metallic layer is chosen from gold or aluminium.

18. A cryostat according to any preceding claim comprising a charge of liquid helium surrounding a SQUID sensor for MRI of NMR scanning.

FIG. 1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Cu (Al, Ag etc.)
Sintered Al_2O_3
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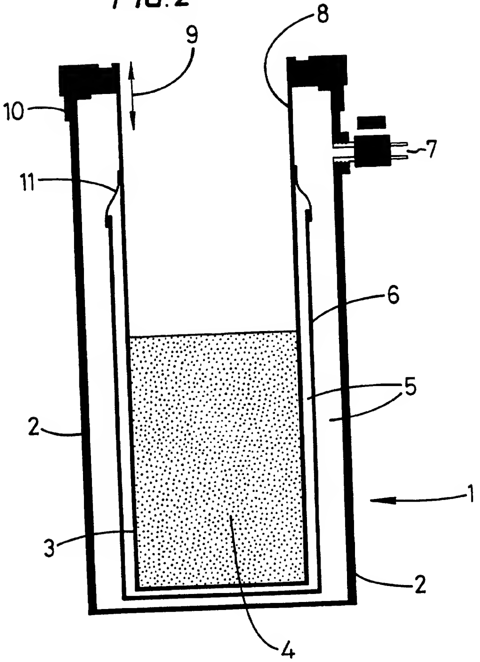
10
1
0.01
0.001
0.0001
Thermal Conductivity
λ (w/cm K)
50
100
T (K)
200
250
300
Temperature °Kelvin

FIG. 2



INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 F17C13/00

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Minimum documentation searched (classification system followed by classification symbols)
IPC 6 F17C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	DE 14 00 921 A (UNION CARBIDE) 30 January 1969 see claims 1-11; figures ---	1-18
Y	WO 94 03754 A (BIOMAGNETIC TECH INC) 17 February 1994 see claims; figures ---	1-18
A	FR 2 530 382 A (THOMSON CSF) 20 January 1984 ---	
A	FR 2 345 658 A (AIR LIQUIDE) 21 October 1977 -----	

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☒ Patent family members are listed in annex.

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1

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Information on patent family members

Inte   onal Application No
PCT/GB 97/02140

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